

INVERTER APPARATUS

CROSS REFERENCE TO RELATED APPLICATION

This is a continuation of U.S. application Serial No. 10/099,973, filed March 19, 2002, the subject matter of which is incorporated by reference
5 herein.

BACKGROUND OF THE INVENTION

The present invention relates to an inverter apparatus for controlling the speed of an induction motor variably.

As a method of controlling an inverter for driving the induction motor
10 so that the induction motor is operated at variable speed, there is known a V/f fixed control method of controlling an output voltage (V_1) of the inverter in proportion to a primary frequency (f_1) of the inverter. This method has a problem that when a load is applied, an induced voltage (E_m) of the motor is reduced because of a voltage drop across a primary resistance (r_1) of the
15 motor, so that a magnetic flux of the motor is made small and accordingly a maximum torque is reduced.

In order to increase a torque in a low and medium speed area, a general inverter includes torque boost function. When a large start torque is required, a boost voltage is set up to a high voltage in a low speed area
20 and the boost voltage is added to a V/f fixed voltage command (induced voltage command E_m^*) to produce an output voltage command of the inverter. However, when the boost voltage is increased, over-excitation occurs in no load. When the over-excitation occurs, the magnetic flux of the motor is saturated and accordingly an excitation reactance is reduced to
25 thereby increase an excitation current. Consequently, the temperature of the motor rises or the current of the inverter is increased excessively, so that there is the possibility that over-current protection function or over-load protection function is operated to be tripped.

A method of suppressing the over-excitation is described in, for example, JP-A-7-163188. In this method, a command for setting up a frequency to zero is issued before start of operation and a DC current is supplied to the motor. An output voltage of the inverter at the time that a
5 current of U-phase becomes equal to an equivalent of a design value of the excitation current is set up as a torque boost voltage ΔV_z0 at the time that the frequency is 0 Hz.

SUMMARY OF THE INVENTION

In the above method, since a torque boost voltage is set up so that
10 the current in no load is equal to a rated excitation current (design value of excitation current), no over-excitation occurs. In this case, however, the voltage drop across the primary resistance is increased when the motor is loaded and accordingly there is a problem that the induced voltage (magnetic flux of motor) is reduced to thereby decrease an output torque.
15 In this manner, heretofore, when the torque boost voltage is made high, the torque is increased, while over-excitation occurs when the load is light. Conversely, when the torque boost voltage is made low, the over-excitation does not occur, while there is an antithetic problem that the torque is not increased.

20 It is an object of the present invention to provide an inverter apparatus suitable for prevention of over-excitation even when a torque boost voltage is set up to be high in order to obtain a large start torque in a general inverter.

In order to achieve the above object, the inverter apparatus
25 according to an aspect of the present invention comprises detection means for detecting an excitation current of the induction motor, setting means for setting a limitation level of the excitation current, torque boost voltage command means for producing a torque boost voltage command in

response to a frequency command of the inverter apparatus, and torque boost voltage compensation means for changing the torque boost voltage command so that the detected excitation current value is smaller than or equal to the excitation current limitation level.

5 The torque boost voltage compensation means includes limiter processing means and inverts the torque boost voltage command. The inverted torque boost voltage command is limiter-processed as a lower limiter value of the limiter processing means to produce a compensation value of the torque boost voltage command.

10 Other objects, features and advantages of the invention will become apparent from the following description of the embodiments of the invention taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram schematically illustrating an embodiment of
15 an inverter apparatus of the present invention;

Fig. 2 is a graph showing a characteristic of a q-axis voltage command V_q^* shown in Fig. 1;

Figs. 3A and 3B are circuit diagrams illustrating a T-type equivalent circuit and an equivalent circuit at a low frequency of an induction motor,
20 respectively;

Figs. 4A and 4B are vector diagrams illustrating output voltages and currents of the inverter in no load and heavy load in the present invention, respectively;

Figs. 5A and 5B are graphs showing an output voltage characteristic
25 and an output current characteristic of the inverter when a torque boost voltage is varied in no load state in the control of the present invention;

Fig. 6 is a block diagram schematically illustrating an inverter apparatus according to another embodiment of the present invention;

Fig. 7 is a block diagram illustrating an I_d (excitation current) detector shown in Fig. 6 in detail; and

Fig. 8 is a graph showing a relation of three-phase voltage commands V_u^* , V_w^* and V_v^* and sections I to VI.

5 DESCRIPTION OF THE EMBODIMENTS

Embodiments of the present invention are now described with reference to the accompanying drawings. In the drawings, like elements are designated by like reference numerals.

Fig. 1 illustrates a control block of an inverter apparatus according to an embodiment of the present invention for controlling the speed of an induction motor variably.

An AC power from an AC power supply 1 is converted into a DC power by means of a rectification circuit 2 and a smoothing capacitor 3. The DC power is converted into an AC variable voltage having a variable frequency by means of an inverter unit 4 to drive an induction motor 5 so that the induction motor is operated at variable speed. An output frequency and an output voltage of the inverter unit 4 are controlled by an inverter control circuit.

In the control circuit of the embodiment, a primary frequency command ω_1^* of the inverter is multiplied by a V/f gain 7 to produce an induced voltage command E_m^* . Further, a torque boost voltage commander 8 produces a torque boost voltage command ΔV_z^* in accordance with the primary frequency command ω_1^* . In this connection, ΔV_z0 is a torque boost voltage set value. Then, the primary frequency command ω_1^* is integrated by an integrator 9 to produce a reference phase command θ_d^* which is a phase reference of the output voltage of the inverter. Further, a uvw/dq converter 11 makes calculation of the equation (1) on the basis of output currents i_u and i_w of a motor current

detector 10 and the reference phase command θ_d^* to detect an excitation current I_d (equivalent of no-load current) of the motor.

$$I_v = -(I_u + I_w)$$

$$I_d = I_u \cdot \cos \theta_d^* + I_v \cdot \cos(\theta_d^* + 2\pi/3) + I_w \cdot \cos(\theta_d^* + 4\pi/3) \quad \dots (1)$$

- 5 Next, a deviation of the an excitation current limitation level command I_{dmax}^* and the detected excitation current value I_d is amplified by a PI (proportion and integration) controller 12 and an output of the controller is supplied to a limiter processing unit 13. The limiter processing unit 13 processes the output of the controller to produce a torque boost
- 10 voltage compensation value ΔV_c . Here, the torque boost voltage command ΔV_z^* is inverted by an inverter [-1] and the inverted torque boost voltage command ΔV_z^* is used as a lower limiter value of the limiter processing unit 13. The lower limiter value is varied in accordance with the primary
- 15 frequency command ω_1^* of the inverter. Further, ΔV_c and ΔV_z^* are added to produce a final compensated torque boost voltage command ΔV_t^* . Then, ΔV_t^* is added to the induced voltage command E_m^* to produce a q-axis voltage command V_q^* of the inverter output voltage. On the other
- 20 hand, a d-axis voltage command V_d^* of the inverter output voltage is calculated by multiplying a rated excitation current command I_d^* by an equivalent of a primary resistance r_1 of the motor in a primary resistance constant circuit 14. Then, a dq/uvw converter 15 is supplied with the rotating coordinate axis components V_d^* and V_q^* of the inverter output voltage command and produces three-phase voltage commands V_u^* , V_v^* and V_w^* for the fixed coordinate axis. This calculation is expressed by the
- 25 equation (2).

$$V_u^* = V_d^* \cdot \cos \theta_d^* - V_q^* \cdot \sin \theta_d^*$$

$$V_w^* = -V_u^*/2 - \sqrt{3}(V_d^* \cdot \sin \theta_d^* + V_q^* \cdot \cos \theta_d^*)/2$$

$$V_v^* = -(V_u^* + V_w^*) \quad \dots (2)$$

Further, a gate signal generator 16 prepares PWM gate signals on the basis of the three-phase voltage commands V_u^* , V_v^* and V_w^* to supply the PMW gate signals to a gate circuit 6.

Fig. 2 shows a range of the q-axis voltage command V_q^* which is the rotating coordinate axis component of the inverter output voltage command.

For example, the magnitude of V_q^* at the primary frequency command $\omega_1^* = \omega_1$ is a value at point a of the induced voltage command E_m^* when the load is zero and since V_q^* is small, the over-excitation can be prevented. On the other hand, when the load is heavy, the magnitude of V_q^* at the primary frequency command is a value at point b of $E_m^* + \Delta V_z^*$ and since V_q^* is large, large torque is obtained. Further, when the load is intermediate thereof, it is a value at point c of $E_m^* + \Delta V_z^* - \Delta V_c$, for example. That is, since the value of $E_m^* + \Delta V_z^*$ at point b is compensated by ΔV_c , it is the value at point c. In this manner, the torque boost voltage compensation value ΔV_c is varied within the range from the point b to the point a in accordance with the load. That is, the torque boost voltage compensation value ΔV_c is varied between upper and lower broken lines.

Incidentally, when there is no limitation control of the excitation current, the torque boost voltage compensation value ΔV_c is 0 and accordingly the upper broken line becomes V_q^* . In the case of V_q^* , over-excitation occurs when the load is light at low speed area. In the embodiment, the limitation control of the excitation current is made so that when the load is light the torque boost voltage compensation value ΔV_c is varied between the upper and lower broken lines to reduce V_q^* so that over-excitation does not occur.

An operation of the embodiment is now described concretely.

First, when the load is lightened or lowered, the detected excitation current value I_d is increased and when the limitation level I_{dmax}^* is exceeded, the PI controller 12 is supplied with a negative value. At this time, the torque boost voltage compensation value ΔV_c becomes also
5 negative. At this time, ΔV_c is functioned to subtract the torque boost voltage command ΔV_z^* so that the final compensated torque boost voltage command ΔV_t^* is controlled to make the excitation current I_d equal to the excitation current limitation level I_{dmax}^* ($I_d = I_{dmax}^*$). Then, when the load is heavy, the excitation current I_d is smaller than the excitation current
10 limitation level I_{dmax}^* ($I_d < I_{dmax}^*$) and accordingly the compensation value ΔV_c is increased from the negative value to be a value of $-\Delta V_z$ to 0. Consequently, the final torque boost voltage command ΔV_t^* becomes 0 to ΔV_z when the load is heavy.

As described above, when the load is light, the final compensated
15 torque boost voltage command ΔV_t^* is reduced so that the excitation current I_d is equal to the excitation current limitation level I_{dmax}^* ($I_d = I_{dmax}^*$) and when the load is heavy, the final compensated torque boost voltage command ΔV_t^* is increased conversely. Since the compensation value ΔV_c is varied within the range of the boost voltage
20 command ΔV_z^* by means of the limiter control unit 13, the final compensated torque boost voltage command ΔV_t^* is operated within the range of $0 \leq \Delta V_t^* \leq \Delta V_z^*$ to thereby prevent excessive compensation.

Operation of the embodiment is now described with reference to an approximate equivalent circuit and voltage and current vector diagrams of
25 the induction motor.

Fig. 3A illustrates a T-type equivalent circuit. r_1 and r_2 represent primary and secondary resistances, x_1 , x_2 and x_m represent primary and secondary leakage reactances and excitation reactance, respectively.

Further, s represents slip. In the low-frequency area in which the torque boost control is required, $x_1 \leq r_1$ and $x_2 \leq r_2/s$. Accordingly, in the low-frequency area, the induction motor can be approximated by the equivalent circuit of Fig. 3B.

5 Figs. 4A and 4B show voltage and current vector diagrams of the motor in no load and heavy load using the approximate equivalent circuit.

In no load, since the slip $s=0$ and the secondary current $I_2=0$, the equivalent circuit becomes a series circuit of r_1 and x_m and the primary current I_1 is equal to the excitation current I_m ($I_1=I_m$). Accordingly, the
10 primary voltage vector V_1 is given by the equation (3), where j represents the imaginary number.

$$V_1 = I_m(r_1 + jx_m) \quad \dots (3)$$

Further, when the d-axis voltage command V_d^* is given by $I_d^* \cdot r_1$ and the q-axis voltage command V_q^* is given by $jI_m \cdot x_m$, the excitation current
15 I_m (no-load current) is approximately equal to I_d shown by the equation (1) and the excitation current I_m can be detected by I_d . I_d^* represents the rated excitation current (no-load current) command.

The broken line of Fig. 4A shows the case where there is no limitation control of the excitation current and the primary voltage V_1' is
20 high. At this time, since the primary voltage V_1' is high, the excitation current I_d ($I_d=I_m'$) is larger than the limitation level I_{dmax}^* , so that over-excitation occurs. The solid line of Fig. 4A shows the case where the limitation control of the excitation current of the embodiment is effective. In this case, since the voltage V_1 is reduced so that $I_d \leq I_{dmax}^*$, the no-load
25 current I_d ($I_d=I_m$) is approximately equal to I_{dmax}^* , so that over-excitation is prevented.

Next, operation in the heavy load is described. In this case, the equivalent circuit is as shown in Fig. 3B and the secondary current I_2 is

increased while the power-factor angle ϕ (angle between V_1 vector and I_1 vector) is decreased. At this time, the induced voltage E_m is greatly reduced as compared with V_1 due to a voltage drop across the primary resistance r_1 and $I_m = I_d < I_{dmax}^*$. At this time, since $I_d < I_{dmax}^*$, the torque
5 boost voltage compensation value ΔV_c becomes 0 ($\Delta V_c = 0$).
Consequently, since the torque boost voltage command ΔV_z^* is added as it is, the inverter output voltage is increased so that reduction of E_m is compensated and the large start torque is obtained.

Fig. 5A and 5B show characteristics of the inverter output current I_1
10 and the inverter output voltage V_1 in the case where the torque boost voltage set value ΔV_{z0} is increased gradually when the output frequency command of the inverter is fixed to a low frequency and the inverter is operated in no load in control of the embodiment.

When there is no limitation control of the excitation current, the
15 output current I_1 and the output voltage V_1 are increased with increase of ΔV_{z0} as shown by broken line. On the other hand, when the embodiment is applied (when the limitation control of the excitation current is effective), the output current I_1 is not increased after the time that the output current I_1 approximately reaches I_{dmax}^* ($I_1 \approx I_{dmax}^*$) as shown by solid line.
20 Consequently, the excitation current (no-load current) is limited and accordingly over-excitation does not occur. Further, as shown by solid line of Fig. 5B, the inverter output voltage V_1 is not also increased and accordingly over-excitation does not occur.

Fig. 6 schematically illustrates another embodiment of the present
25 invention. This embodiment is different from the embodiment of Fig. 1 in that the excitation current I_d is detected from the inverter input current i_{dc} . The excitation current I_d is detected on the basis of an output signal i_{dc} of

an inverter input current detector 17, the gate signal of the inverter and the reference phase command θ_d^* in an excitation current detector 18.

Fig. 7 illustrates a detail configuration of the excitation current detector 18. The excitation current detector 18 is composed of a sample-and-hold signal preparation circuit 19, a sample-and-hold circuits 20a and 20b and an I_d arithmetic unit 21. The sample-and-hold signal preparation circuit 19 produces a sample-and-hold signals SHa and SHb on the basis of PWM gate signals by means of logical AND circuits 22 and logical OR circuits 23 as shown in Fig. 7. In the circuit of Fig. 7, the inverter input current i_{dc} is sampled and held in the switching mode that only one phase gate signal of three-phase gate signals is turned on to be outputted as an i_a signal. Further, in the switching mode that only two phases are turned on, i_{dc} is sampled and held to be outputted as an i_b signal. Then, the I_d arithmetic unit 21 performs calculation of the equation (4) to produce I_d .

Fig. 8 shows a relation of waveforms of three-phase voltage commands V_u^* , V_w^* and V_v^* and sections I to VI.

In the section I, $V_u^* \geq V_w^* > V_v^*$,

$$i_\alpha = -i_a, i_\beta = (i_a - 2i_b)/\sqrt{3},$$

$$I_d = i_\alpha \cdot \cos(\theta_d^* - 2\pi/3) + i_\beta \cdot \sin(\theta_d^* - 2\pi/3)$$

In the section II, $V_u^* \geq V_v^* > V_w^*$,

$$i_\alpha = i_b, i_\beta = (2i_a - i_b)/\sqrt{3},$$

$$I_d = i_\alpha \cdot \cos \theta_d^* + i_\beta \cdot \sin \theta_d^*$$

In the section III, $V_v^* \geq V_u^* > V_w^*$,

$$i_\alpha = -i_a, i_\beta = (i_a - 2i_b)/\sqrt{3},$$

$$I_d = i_\alpha \cdot \cos(\theta_d^* - 4\pi/3) + i_\beta \cdot \sin(\theta_d^* - 4\pi/3)$$

In the section IV, $V_v^* \geq V_w^* > V_u^*$,

$$i_\alpha = i_b, i_\beta = (2i_b - i_a)/\sqrt{3},$$

$$I_d = i_\alpha \cdot \cos(\theta_d^* - 2\pi/3) + i_\beta \cdot \sin(\theta_d^* - 2\pi/3)$$

In the section V, $V_w^* \geq V_v^* > V_u^*$,

$i_\alpha = -i_a$, $i_\beta = (i_a - 2i_b)/\sqrt{3}$,

$I_d = i_\alpha \cdot \cos \theta_d^* + i_\beta \cdot \sin \theta_d^*$

In the section VI, $V_w^* \geq V_u^* > V_v^*$,

5 $i_\alpha = i_b$, $i_\beta = (2i_b - i_a)/\sqrt{3}$,

$I_d = i_\alpha \cdot \cos(\theta_d^* - 4\pi/3) + i_\beta \cdot \sin(\theta_d^* - 4\pi/3) \quad \dots(4)$

Discrimination of the 60-degree sections I to VI is made on the basis of the magnitude of the three-phase voltage commands produced by the dq/uvw converter 15. Further, the discrimination of the 60-degree sections I to VI can be also made similarly by using the voltage command phase θ_d^* . The system for detecting the excitation current I_d from the DC current i_{dc} is described in JP-A-2001-314090 in detail.

In the embodiment of Fig. 6, only one inverter input current detector 17 may be used to detect the excitation current I_d and the motor current detector (for two phases) as shown in the embodiment of Fig. 1 is not required, so that the inverter apparatus can be configured inexpensively.

As described above, according to the embodiment, since the torque boost voltage can be adjusted automatically so that the excitation current is smaller than or equal to the limitation level even when the torque boost voltage is set up to be large in the torque boost control of the inverter, over-excitation does not occur in light load. Furthermore, since the torque boost voltage can be set up to be high, large start torque can be obtained even in heavy load.

Further, since over-excitation does not occur even when the torque boost voltage is set up to be high, it is not necessary to adjust the torque boost voltage in accordance with the magnitude of load. Accordingly, adjustment is not required and handling is good.

It should be further understood by those skilled in the art that the foregoing description has been made on embodiments of the invention and that various changes and modifications may be made in the invention without departing from the spirit of the invention and the scope of the
5 appended claims.